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Friedel-Crafts Alkylation I. Kinetics of the $\text{AlCl}_3 \cdot \text{CH}_3\text{NO}_2$ -Catalyzed Phenethylation of Benzene and Toluene in Nitromethane*

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The kinetics of the $\text{AlCl}_3 \cdot \text{CH}_3\text{NO}_2$ -catalyzed phenethylation of benzene and toluene with phenethyl chloride in homogeneous nitromethane solution have been investigated at 50°C, utilizing gas chromatography to follow the reaction. The rate data reveal that the reaction is first-order in the aromatic, first-order in the chloride, and second-order in the catalyst. The relative reactivity of toluene to benzene was also determined in competitive experiments. The low substrate and positional selectivities were observed. The phenethylation of benzene- d_6 showed no primary kinetic isotope effect. The mechanism of the reaction is discussed in the light of the experimental results.

INTRODUCTION

Numerous investigations have been focused on the mechanism of the Friedel-Crafts alkylation of aromatic compounds with primary alkyl halides.¹⁾ Brown and co-workers²⁾ proposed that the reaction proceeded by a displacement mechanism involving nucleophilic attack by the aromatic component on the alkyl halide-Lewis acid catalyst addition compound. The first-order dependence on the aromatic substrate was repeatedly confirmed.³⁾

Recently, McMahon and Bunce⁴⁾ have alkylated toluene in the presence of aluminum chloride with 2-phenylethyl-1- C^{14} chloride, and suggested the formation of a symmetrical intermediate. Unfortunately, the complexity of the system prevented the kinetic study of the reaction and there was no mention of the isomer distribution of 1-phenyl-2-tolyethanes formed.

At present there are few reports^{4,5)} on the Friedel-Crafts alkylation with 2-aryl-ethyl chlorides. Therefore kinetic studies with ring-substituted phenethyl chlorides will be made to elucidate the alkylation mechanism. This paper reports a kinetic investigation of the reaction of benzene and toluene with phenethyl chloride in nitromethane solution, primarily to determine the exact rate law. Aluminum chloride dissolved in the solvent was used as the catalyst. Reaction rates were calculated by determining the amounts of unreacted phenethyl chloride and 1,2-diphenylethane or 1-phenyl-2-tolyethanes produced.

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EXPERIMENTAL

Materials. Benzene, toluene, cyclohexane, and phenethyl chloride were commercial products of highest available purity. They were further purified by distillation. Nitromethane was purified according to Olah, *et al.*⁶⁾ Benzene- d_6 was obtained from Merck Co. 1,2-Diphenylethane and 1-phenyl-2-tolyethanes were prepared by previously described methods.⁷⁾ 1,1-Diphenylethane was prepared according to the method of Reichert and Nieuwland.⁸⁾ Hydroquinone diisopropyl ether used as the internal standard in gas chromatographic analyses was prepared from hydroquinone and isopropyl bromide in the usual way.⁹⁾ The purity of the reference materials (greater than 99.8% pure) was checked by gas chromatography and infrared spectra. Commercial aluminum chloride was sublimed before use. This product was always handled and stored under dry nitrogen.

General procedure for the kinetic measurement. Molar solutions in nitromethane of aluminum chloride and phenethyl chloride were prepared. An aliquot of the aluminum chloride solution and a desired amount of aromatic hydrocarbon (benzene, benzene- d_6 , or toluene) were transferred into a 100-ml, three-necked flask equipped with a reflux condenser, a thermometer, and a stopcock. The flask was then placed into a constant temperature bath ($50 \pm 0.1^\circ\text{C}$), and a desired amount of the phenethyl chloride solution, maintained at the reaction temperature, was syringed through the stopcock into the flask with magnetic stirring. Small portions (ca. 2 ml) of the reaction mixture was syringed out quickly at intervals. Each sample was quenched with ice-water, washed with a small amount of water, then dried over anhydrous Na_2SO_4 , and analyzed by gas chromatography. In order to calculate the concentrations of the reactants and the catalyst, the solution was assumed to be ideal.

Competitive phenethylation. A mixture of equimolar amounts of benzene (or benzene- d_6) and toluene was phenethylated in nitromethane solution at 50°C in the same manner as described above. The samples were taken periodically and analyzed by gas chromatography.

Analytical procedure. The analyses were carried out by using a Hitachi Perkin-Elmer Model F6 gas chromatograph. A Golay capillary column (length 90 m, i. d. 0.50 mm) coated with butanediol succinate polyester was used with a hydrogen flame ionization detector. The column temperature of 155°C and the nitrogen carrier gas pressure of 1.2 Kg/cm^2 were employed for all measurements. After determination of relative response data, mol% were calculated from the areas of individual peaks for the products by the internal standard method. The accuracy of measurements was found to be within the limit of $\pm 3.0\%$ relative error, based on analyses of mixtures of known compositions.

RESULTS AND DISCUSSION

Aluminum chloride is known to form a very stable 1 : 1 addition complex with nitromethane which is a quite soluble alkylating catalyst and effects isomerization to a lesser extent than does aluminum chloride alone in aromatic hydrocarbon solvents.¹⁰⁾ This complex formation, however, decreases the activity of aluminum chloride and

hence higher temperatures are required. Preliminary experiments showed that at temperatures near 50°C phenethylation proceeded at a convenient rate to follow the reaction. Details of the procedures of the phenethylations are given in the experimental part. Under the experimental conditions employed, di- or higher alkylation of benzene and toluene was negligible, but in the case of benzene the rearranged product, 1,1-diphenylethane, was detected in substantial quantities (about 4–12 mol% at 80% conversion). The amount of the by-product increased with an increase in temperature or in mole ratio of phenethyl chloride to benzene. Therefore, reaction rates were determined preferably before less than 4 mol% of the by-product were formed.

The kinetic study of the reaction with benzene and toluene reveals that the reaction is first-order in the chloride and first-order in the aromatic component. Pseudo-second-order rate plots are shown in Figure 1. Rate data for the phenethylation of benzene are summarized in Table 1. In order to determine the reaction order with respect to the catalyst, higher order rate constants were calculated by dividing the values of k_2 by successive powers of the initial aluminum chloride concentration. Since the fourth-order rate constants k_4 show the most constancy, it is considered that the reaction is second-order with respect to the catalyst. Therefore, the rate expression is

$$\text{Rate} = k_4 [\text{AlCl}_3]^2 [\text{C}_6\text{H}_6] [\text{PhCH}_2\text{CH}_2\text{Cl}] \quad (1)$$

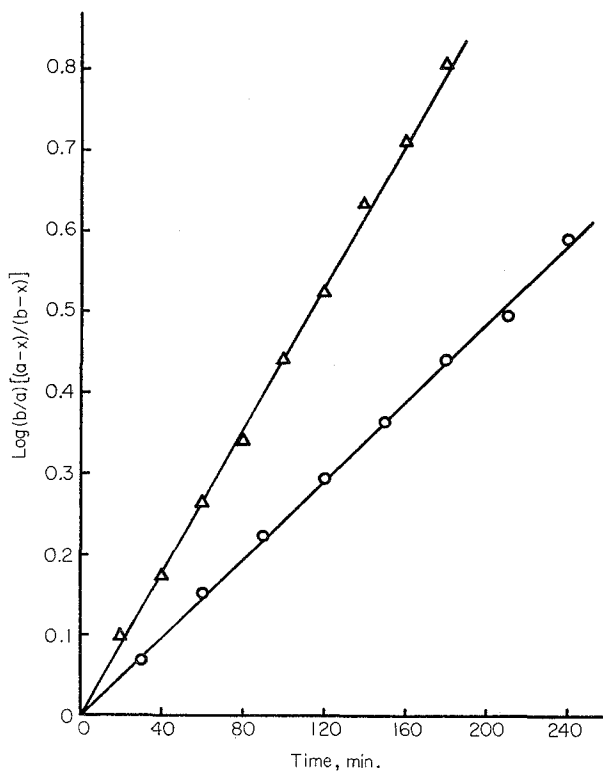


Fig. 1. Phenethylation of benzene (○) and toluene (Δ) in nitromethane solution at 50°C (Initial concentration, benzene: toluene=1.19 : 1.00)

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Table 1. Summary of Rate Data for the Reaction of Benzene with Phenethyl Chloride and Aluminum Chloride in Nitromethane Solution.

Run No.	Temp. (°C)	Initial concentrations (mol/l)			Rate constants		
		AlCl ₃	PhCH ₂ CH ₂ Cl	C ₆ H ₆	k ₂ × 10 ^{3 a)}	k ₃ × 10 ^{3 b)}	k ₄ × 10 ^{2 c)}
1	50.0	0.400	0.400	2.24	2.95	7.38	1.84
2	"	"	"	" d)	3.02	7.55	1.89
3	"	"	0.200	"	2.86	7.15	1.79
4 e)	"	"	"	"	2.17	5.43	1.37
5	"	0.300	0.300	0.400	1.57	5.23	1.74
6	"	0.200	0.400	2.24	0.626	3.13	1.56
7	"	"	0.200	"	0.836	4.18	2.09
8	"	"	0.400	1.12	0.847	4.24	2.12
9	"	"	0.200	0.600	0.688	3.44	1.72
10	"	0.100	0.400	2.24	0.181	1.81	1.81
11	"	"	0.200	4.48	0.143	1.43	1.43
12	48.8	0.400	0.400	2.24	2.31		
13	40.0	"	"	"	0.790		
14	25.0	"	"	"	0.0973		

a) Second-order rate constants (1 mol⁻¹ min⁻¹).

b) k₃=k₂/[AlCl₃] 1² mol⁻² min⁻¹.

c) k₄=k₂/[AlCl₃]² 1³ mol⁻³ min⁻¹.

d) Benzene-d₆ was used.

e) Cyclohexane (1.85 mol/l) was added.

Table 2. The Reaction of Benzene and Toluene with Phenethyl Chloride and Aluminium Chloride in Nitromethane Solution.

Run No.	Temp. (°C)	Initial concentrations (mol/l)				k ₂ × 10 ^{3 a)}	k _T /k _B	PTE(%) b)		
		AlCl ₃	PhCH ₂ CH ₂ Cl	C ₆ H ₆	C ₆ H ₅ CH ₃			ortho	meta	para
1	50.0	0.400	0.400		1.88	7.00	2.37	49.4	19.1	31.5
2	"	0.200	"		"	1.53	2.44	49.2	19.5	31.3
3	25.0	0.400	"		"	0.242	2.58	49.2	19.3	31.5
4	50.0	"	"	1.02	1.02		3.18 c)	49.5	19.4	31.1
5	"	0.313	0.313	1.56	1.56		3.31 d)	48.7	19.8	31.5
6	"	"	"	" e)	"		3.21 d)	49.1	19.5	31.4

1-3; Noncompetitive phenethylations. The values of k_T/k_B were calculated by using the data in Table 1, that is, k_T/k_B=k₂(toluene)/k₂(benzene).

4-6; Competitive phenethylations.

a) Second-order rate constants (1 mol⁻¹ min⁻¹).

b) 1-Phenyl-2-tolyethanes.

c) k_T/k_B=log [1-PTE]/[C₆H₅CH₃]₀/log [1-DPE]/[C₆H₆]₀, where DPE is 1,2-diphenylethane and [C₆H₆]₀, [C₆H₅CH₃]₀ are initial concentrations.

d) k_T/k_B=PTE/DPE.

e) Benzene-d₆ was used.

Table 3. The Competitive Phenethylation of Benzene and Toluene at 50°C (Table 2, Run 5).

Time min.	PhCH ₂ CH ₂ Cl reacted %	k _T /k _B	1-Phenyl-2-tolyethanes (%)		
			ortho	meta	para
20	18.9	3.47	48.2	20.3	31.5
40	32.4	3.40	48.4	20.0	31.6
60	42.0	3.31	48.5	20.1	31.4
80	51.1	3.32	48.8	19.7	31.5
100	58.9	3.27	48.7	19.6	31.7
120	64.7	3.30	49.3	19.4	31.3
140	69.2	3.19	49.3	19.7	31.0
160	74.0	3.19	48.7	19.7	31.6
Average		3.31	48.7	19.8	31.5

The reaction with toluene is also second-order in the catalyst. The isomer distributions of 1-phenyl-2-tolyethanes together with the relative rates of toluene to benzene, k_T/k_B , are summarized in Table 2. Table 3 shows a representative experiment of the competitive phenethylations. In order to clarify whether consecutive isomerization existed or not, a small amount of pure *o*-, *m*-, or *p*-isomer was added to the reaction mixture. No isomerization was observed. Further, it was already shown that ring protonation (σ -complex formation) with $AlBr_3 \cdot HBr$ did not occur in nitromethane solution.⁷⁾ From these results it is believed that practically non-isomerizing conditions were present for this investigation, unless the concurrent isomerization in the proposed activated state for the alkylation is considered.¹¹⁾

Assuming that the relative response of 1,2-diphenylethane- d_6 was equal to that of 1,2-diphenylethane, the determination of the kinetic isotope effect was carried out by gas chromatography. The phenethylation of benzene- d_6 (Table 1, Run 2) shows no primary kinetic isotope effect, that is, $k_H/k_D=0.977$. In the case of competitive phenethylation (Table 2, Run 6) also no isotope effect was observed.

$$k_{Toluene}/k_{Benzene} = 3.31$$

$$k_{Toluene}/k_{Benzene-d_6} = 3.21$$

And hence, $k_H/k_D=0.970$.

This indicates clearly that the elimination of hydrogen is not involved in the rate-determining step. As to the secondary isotope effect which is usually very small,^{3b)} however, it is impossible to discuss its existence, owing to unavoidable uncertainty in the experiments.

In contrast with the benzylation reaction by Olah, *et al.*^{3b)} which showed low substrate, but high positional selectivity, the present phenethylation gave a result which obeyed Brown's selectivity relationship. Partial rate factors calculated from the data (Table 3) are as follows;

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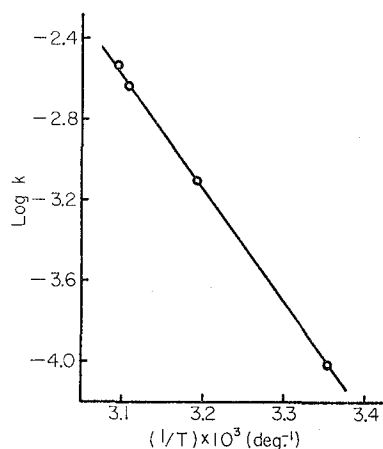


Fig. 2. Arrhenius plot for the phenethylation of benzene in nitromethane solution.

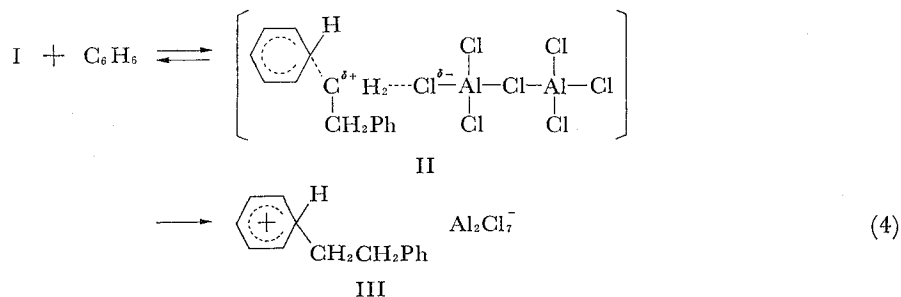
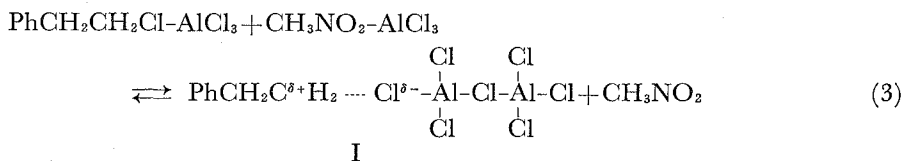
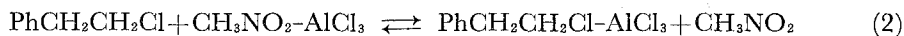
$$o_i = 4.84, \quad m_i = 1.97, \quad \text{and} \quad p_i = 6.26$$

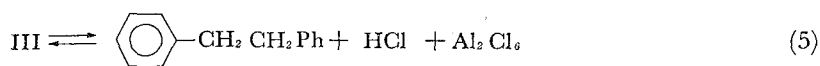
These values provided a fairly good fit with the relationship. But the activated complex in the rate-determining step should be considered closer to a π -complex in nature than to a σ -complex.¹²⁾

The values of k_T/k_B in noncompetitive experiments were slightly smaller than those obtained in competitive ones. This suggests that the substrate-catalyst complex may take part in the reactions with toluene which is stronger base than benzene. Thus it is thought that the acid strength in toluene is slightly lowered compared with that in benzene.

The Arrhenius plot for the phenethylation of benzene is shown in Figure 2. The apparent energy of activation for the reaction was calculated from the slope. $E_a = 25.9$ Kcal/mol. With toluene, $E_a = 25.8$ Kcal/mol, by using the data in Table 2.

The mechanism which is consistent with the rate expression (1) can be proposed for the $\text{AlCl}_3 \cdot \text{CH}_3\text{NO}_2$ -catalyzed phenethylation of benzene in nitromethane solution.



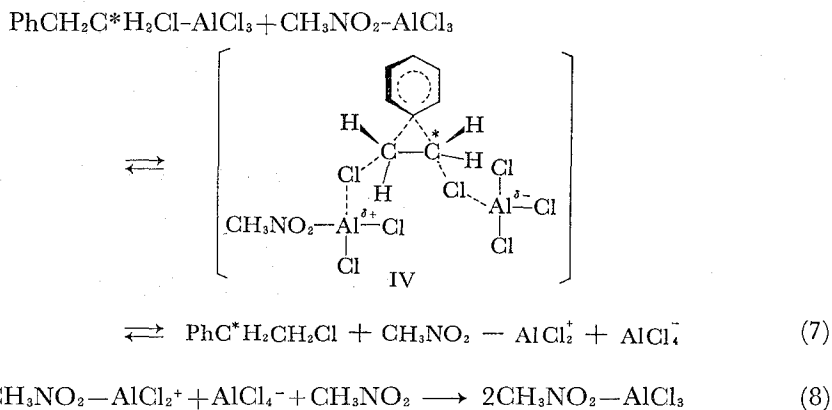


With step (4) rate determining, the appropriate rate law should be

$$-\frac{d[\text{C}_6\text{H}_5]}{dt} = k_4[\text{CH}_3\text{NO}_2\text{-AlCl}_3]^2 [\text{C}_6\text{H}_5] [\text{PhCH}_2\text{CH}_2\text{Cl}] \quad (6)$$

Assuming that all of the catalyst exist as $\text{CH}_3\text{NO}_2\text{-AlCl}_3$ complex, the rate law (6) is in substantial agreement with (1). Second-order dependence on the catalyst is not unusual.^{3a)} It seems reasonable to consider that the weaker Lewis acid such as the present catalyst requires the assistance of a second molecule of the catalyst to effect transfer of the alkyl group from the 1 : 1 complex, RCl-AlCl_3 , to the aromatic. Because of the difficulty to break the C-Cl bond, RCl is considered to be only polarized in the rate-determining step. Therefore, the reaction would not proceed via phenonium ion-type intermediate,⁴⁾ but occur by way of a concerted displacement of the aromatic substrate on the phenethyl chloride-aluminum chloride system (Equation (4)). The polarized structure of the alkylating agent is also substantiated by the fact that changes in dielectric constant of the reaction system do not cause a significant decrease or increase in reaction rate (Table 1, Runs 4 and 5). In addition, if phenyl participation may occur, somewhat lower substrate selectivity would be observed, since this ion is considered to be more reactive than the polarized intermediate.

The phenyl migration in phenethyl chloride may be caused by the attack of a second molecule of the catalyst on the addition complex of phenethyl chloride and aluminum chloride.



The activated state in the rearrangement may look like IV, which is analogous to the transition state in the rearrangement of cyclopropylcarbinyl chloride to cyclobutyl chloride in the presence of aluminum chloride in nitromethane solution.¹³⁾ If $\text{S}_\text{N}2'$ reaction such as (7) is much slower than the alkylation, then it is possible to exchange the carbon atoms without altering the rate expression (6). And if it were the case, the phenethylation in nitromethane solution would be different from that in toluene which showed no isotopic rearrangement in phenethyl chloride recovered.⁴⁾

The hydride shift in the phenethylation process which gives a more stable cation than $\text{PhCH}_2\text{CH}_2^+$ is responsible for the formation of the rearranged product. It seems that the shift which may occur in the addition complex I is competing with the faster alkylation, and that in the case of the phenethylation with toluene it is much slower than the reaction of I with toluene. The occurrence of the hydride shift suggests the probability of the phenyl migration and no participation of the phenonium ion which has a rigid structure. Unfortunately, lack of experimental data with carbon-14 remains it equivocal to establish whether or not the exchange reaction of homobenzylic carbon atoms actually takes place.

Studies of effects of substituents on reaction rates and isomer distributions, and of rearrangement reactions will be reported later.

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